FURTHER STUDY OF THE T PHASE*

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ABSTRACT

New data are presented in support of the conclusion that the T phase is propagated across oceans as compressional waves in the water. T phases from many circumpacific-belt shocks were recorded at the Honolulu seismograph station and at the Kaneohe and Point Sur SOFAR Stations, permitting the determination of oceanic velocity by simple division of epicentral distance by travel time since correction for land travel was unnecessary. The signals were much sharper and less prolonged than those previously studied. Very little scatter in the velocity was observed. Divergent views on the nature of T reported by other investigators are due to complications in path, travel time, and land correction introduced by the relatively large proportion of land (or shallow water) paths involved in the shocks which they have studied.

Introduction

The T phase is a train of waves of period between about ½ and possibly 1/100 second propagated across ocean basins from earthquakes having epicenters in the basin or very near its margin, and received on seismographs on islands or near the coast. In an earlier paper[1] it was concluded that the T phase represents sound energy introduced into the ocean near the epicenter and transmitted as compressional waves in the water over the oceanic part of the path. In the first paper two approximations were made: (1) the velocity in the continental part of each path was taken as that of compressional waves in typical continental rock; and (2) refraction effects, both lateral and vertical, at the continental margins were ignored. The build-up and decay times varied from a few tens of seconds to several minutes, being greater where a considerable amount of continental travel was involved, and also greater for large shocks than for small ones. Any determination of the velocity of T across the ocean depends on the correction applied for travel across land. This correction is extremely difficult to ascertain because of the complex layering of the continental crust and the multiple refraction paths resulting from propagation across an irregular continental margin. The gradual build-up of T for paths with considerable continental travel introduces uncertainty in the true travel time of the phase.

In view of these approximations it is clear that the best way to determine the velocity of T across the ocean is to select epicenters and detector locations with respect to which the correction for the continental part of the path is negligible or very small and the signal duration is brief. We now present new material chosen with this purpose in mind. Many shocks from the circumpacific belt produced T phases at the Honolulu seismograph station and at the Kaneohe and Point Sur SOFAR stations, all of which required no correction for land travel and permitted determination of velocity by simple division of epicentral distance by travel time. These signals were much sharper and less prolonged than those previously studied, the maximum could be picked with an uncertainty of less than ten seconds, the duration was usually less than one minute, and the distances were large to such a

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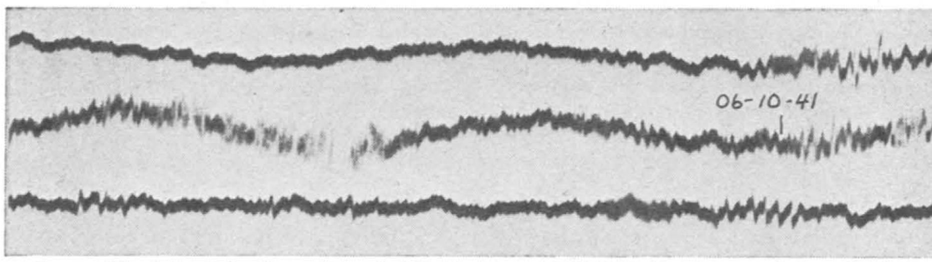
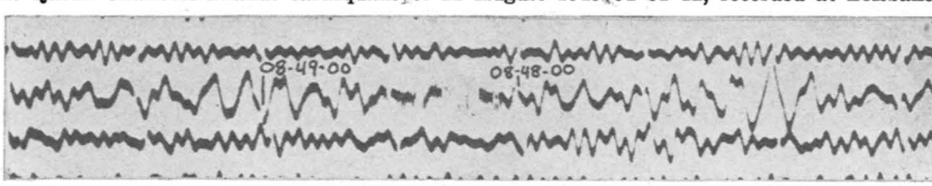
[1] Ivan Tolstoy and Maurice Ewing, "The T phase of Shallow-Focus Earthquakes," *Bull. Seism. Soc. Am.*, 40:25–51 (1950).

degree that a change in velocity of one per cent or less would have been introduced by using the arrival time of the first detectable signal. A small amount of additional material was available for Atlantic shocks recorded by seismographs on Bermuda.

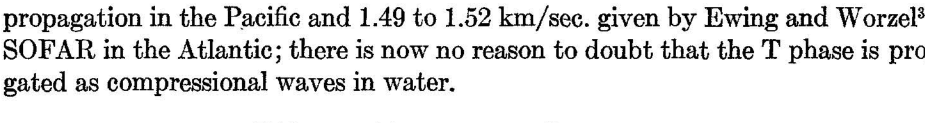
For 27 circumpacific shocks recorded on the Honolulu or Brisbane seismographs the mean velocity was 1.49± .02 km/sec. For 15 shocks with reasonably good preliminary epicenters recorded at the SOFAR stations the mean velocity was 1.47± .01 km/sec. All other observations reported below are consistent with these velocities. The velocities agree well with 1.48 km/sec. given by Anderson[2] for SOFAR



a. Queen Charlotte Islands earthquake of 22 August 1949, 04–01–12, recorded at Brisbane.



b. Dominican Republic earthquake of 26 July 1950 08–31–28, recorded at Bermuda.



c. Solomon Islands earthquake of 29 July 1950 23–48–58, recorded at Honolulu.

Fig. 1. Typical T phases recorded on seismographs.

propagation in the Pacific and 1.49 to 1.52 km/sec. given by Ewing and Worzel[3] for SOFAR in the Atlantic; there is now no reason to doubt that the T phase is propagated as compressional waves in water.

T Phases Recorded by Seismographs

Figure 1 shows typical T-phase seismograms: *a* was recorded on the Brisbane Benioff vertical from the Queen Charlotte Island shock of 22 August 1949, at an epicentral distance of 11,550 km.; *b* was recorded on a Sprengnether horizontal of the Bermuda tripartite microseism station from the Dominican Republic shock of 25 July 1950, at a distance of about 1,430 km.; and *c* was recorded on the Honolulu Neumann-Labarre from the Solomon Islands shock of 29 July 1950 at a distance of about 5,960 km.

[2] E. R. Anderson, "Distribution of Sound Velocity in a Section of the Eastern North Pacific," *Trans. Am. Geophys. Union*, 31: 221–228 (1950).

[3] Maurice Ewing and J. L. Worzel, "Long-Range Sound Transmission," in Geol. Soc. Am., *Memoir 27* (1948).

Table 1 gives the relevant data about all T phases found in a search of the Honolulu seismograms for a two-year period. Additional material from Brisbane is included, as well as a summary of results previously reported. The mean T-phase velocity for the shocks recorded at Honolulu and Brisbane is 1.49 ± 0.02 km/sec. The propagation paths are indicated in figure 2. Several T phases from Atlantic shocks recorded on Bermuda seismographs are listed in table 2. Velocities computed for the first three shocks are uncertain since epicenters and origin times for these tremors are poorly determined because of their small size. In fact, it would be more logical to use the T phase for epicenter location than for velocity determination in these cases. A more complete study of Atlantic T phases recorded on Bermuda will be presented at a later date.

T Phases Recorded by SOFAR Station

SOFAR is the name which has been coined by the U. S. Navy for the long-distance transmission of sound between a source and a receiver in the ocean at the depth of minimum sound velocity. A typical SOFAR signal from the explosion of a small bomb at a depth of 4,000 feet received by a hydrophone at a depth of 3,600 feet 300 miles away is shown in figure 3. It is seen that the intensity increases gradually for about four seconds to a sharp maximum and ends abruptly. This maximum corresponds to sound which has traveled horizontally at the depth of minimum sound velocity, and it is standard practice to read the travel time of this maximum rather than the beginning of the signal for use in calculations of distance.

SOFAR records covering intermittent monitoring by the SOFAR stations at Point Sur and Kaneohe were examined for signals generated by earthquakes, and 21 signals were found as listed in table 3. The paths of these T phases are shown in figure 4. In addition, numerous signals were observed which could not be correlated with any reported earthquakes and may have originated in tremors too small for observation by seismographs.

Figure 5, *a*, *b*, *c*, *d*, shows typical T phase records recorded at the Kaneohe, Oahu, SOFAR station from earthquakes off the Aleutian Islands, California, Mexico, and the Queen Charlotte Islands. Figure 6, *a*, *b*, *c*, shows T phases recorded at the Point Sur, California, SOFAR station for shocks in the New Hebrides, the Solomon Islands, and off California. These records give a measure of the sound intensity as detected by a hydrophone at a depth of several hundred fathoms. The deflection of the trace is proportional to the logarithm of the intensity.

In determining the average velocity we have not used the data for shocks 6, 11, 12, 21, since accurate epicenter determinations are not available. Here again, it would be better to use the signal travel time to determine the epicenter than to use it to determine the velocity of propagation. The mean velocity for the remaining 17 signals is 1.46 ± .02 km/sec. It is to be noted that shocks 13 and 14, which occurred on the same day at the same place, gave velocities significantly lower than all others and in particular lower than other shocks in the same area. It is believed that these low velocities are due to an error (which we have been unable to locate) either in location of the epicenter or, more probably, in the timing at the SOFAR station. Excluding these values, we obtain a mean velocity of 1.47 ± .01 km/sec. for the T phase from the remaining 15 shocks.

TABLE 1

PACIFIC T PHASES RECORDED ON SEISMOGRAPHS

Station	No.	Date	G.C.T. origin time	Latitude	Longitude	Magnitude	Focal depth	Δ	Travel time	Velocity
				degrees	degrees			km.	sec.	km/sec.
Honolulu	1	9 Sept. '50	10–21–40	4 S	153 E	6¼	...	6,033	4,090	1.48
Honolulu	2	31 Oct. '49	17–55–35	5 S	152½ E	...	100	6,125	4,055	1.51
Honolulu	3	4 Dec. '50	16–28–01	5 S	153½ E	7	100	6,044	4,049	1.49
									4,119	1.47
Honolulu	4	20 Oct. '49	12–44–54	5½ S	154 E	6½	. .	6,025	4,067	1.48
									4,136	1.46
Honolulu	5	20 Oct. '49	21–00–11	5½ S	154 E	6¾	.	6,025	4,099	1 47
									4,154	1.45
Honolulu	6	24 Sept. '49	04–17–38	6 S	154 E	7	...	6,055	4,027	1.50
Honolulu	7	29 July '50	23–48–58	6 S	155 E	7	..	5,956	4,012	1.48
Honolulu	8	8 Nov. '50	02–18–09	9½ S	159½ E	7¼–7½	...	5,764	3,751	1.54
									3,821	1.51
Honolulu	9	28 Oct. '49	06–31–51	10 S	160 E	...	..	5,755	3,794	1.52
Honolulu	10	15 Oct. '50	15–54–53	10 S	160 E	6½		5,755	3,817	1.51
Honolulu	11	28 July '50	05–23–21	13 S	167 E	..	.	5,391	3,639	1.48
Honolulu	12	28 July '50	04–55–13	13 S	167 E	. .	...	5,391	3,637	1.48
Honolulu	13	7 Nov. '49	05–59–35	14 S	166½ E	6¾	...	5,517	3,705	1.49
Honolulu	14	10 Sept. '50	15–15–57	14 S	167 E	7	...	5,469	3,763	1.45
Honolulu	15	21 July '50	20–32–01	15½ S	168 E	...		5,513	3,749	1.47
Honolulu	16	2 Dec. '50	19–51–45	18 S	167 E	7½–8	...	5,786	3,815	1.52
Honolulu	17	20 July '50	09–30–48	17 S	174 E	.	.	5,225	3,600±	1.45
Honolulu	18	6 Aug. '49	00–35–27	19 S	174½ W	7½	. .	4,805	3,223	1.49
Honolulu	19	22 Nov. '49	00–51–32	29 S	178 W	7¼–7½	...	5,962	3,998	1.49
Honolulu	20	27 Nov. '49	08–42–16	18 S	173 W	...	..	4,642	2,914	1.59
Honolulu	21	23 Aug. '49	20–24–32	53 N	132 W	6¼	..	4,150	2,808	1.48
Honolulu	22	22 Aug. '49	04–01–12	54 N	133 W	8		4,190	2,823	1.48
Brisbane	22a	22 Aug. '49	04–01–12	54 N	133 W	8	..	11,550	7,768	1.49
Honolulu	23	31 Oct. '49	01–39–32	56 N	135 W	6¾	...	4,288	2,903	1.48

TABLE 1 — *Continued*

Station	No.	Date	G.C.T. origin time	Latitude	Longitude	Magnitude	Focal depth	Δ	Travel time	Velocity
				degrees	degrees			km.	sec.	km/sec.
Honolulu.........	24	25 Aug. '49	04–14–15	52½ N	178 W	6½	Deeper than normal	3,869	2,585 2,630	1 45 1.47
Honolulu	25	3 Nov. '49	01–12–37	48½ N	154 E	6¾–7	200	5,211	3,533	1.47
Honolulu.	29a [a]	14 May '48	22–31–42	54½ N	161 W	8	...	3,692	2,456	1.50
Pasadena.. ...	26 [a]	23 Jan. '38	08–32–43	21 N	156 W	6¾	..	3,975	2,591	1.53
Riverside..... .	27 [a]	20 Dec. '46	19–19–05	32½ N	134½ E	8.2		9,469	6,191	1.53
Tinemaha...... ..	28 [a]	10 Nov. '38	20–18–42	55½ N	158 W	8¼	..	3,600	2,125	1.69
Mineral	29 [a]	14 May '48	22–31–42	54½ N	161 W	8	.	3,295	2,245	1.47
Tinemaha.	30 [a]	7 Dec. '44	04–35–42	33 N	136 E	8	...	9,058	5,943	1.52
Tinemaha.	31 [a]	2 Mar. '33	17–31–00	39 N	144½ E	8¼	. .	8,049	5,331	1.51

[a] From Tolstoy and Ewing, *Bull. Seism. Soc. Am.*, 40: 25–51 (1950).

It is interesting to note that earthquakes southwest of Honolulu which produced T phases on the seismographs there did not produce signals on the SOFAR hydrophone, which is situated a short distance northeast of the same island. Thus the island of Oahu casts a shadow for the T phase from earthquakes exactly like that cast by Bermuda for SOFAR signals, as described by Ewing *et al.*[4] This is additional evidence in support of the view that the T phase is propagated as a compressional wave in the water.

It has been shown theoretically[5] that the efficiency of an earthquake in exciting the T phase decreases rapidly as the depth of focus increases if the ocean floor at the epicenter is level, but that an ocean floor which deepens in the direction of propagation of the T phase can permit entry of the sound waves into the water with travel along near-horizontal rays as required for wave-guide propagation[6] (analogous to use of a prism to introduce light into a plate in the Lummer-Gehrcke interferometer). As is well known, the precise depth of focus of an earthquake is difficult to obtain from seismological evidence, particularly for oceanic epicenters, when data from an enclosing network of near-by seismographic stations are not available. Hence it is not surprising that the intensity of the T phase is not determined by the magnitude of the earthquake alone. For example, some small shocks which are only barely detectable by the Berkeley seismographs give much stronger T phases on the Kaneohe SOFAR hydrophone than shocks of magnitude 6¼–6½ in other regions at comparable distances (e.g., shocks 4 and 6, table 3). This illustrates the potentialities of the T phase as an effective tool for investigating details of the action at the focus, in addition to its value for precise location of epicenters. Over almost all of the circumpacific belt, earthquakes of this magnitude are undetected, being beyond the range of the small number of sensitive seismographs which are situated near it; yet their T phase could be detected almost anywhere in the Pacific Ocean.

TABLE 2

SOME RECENT ATLANTIC T PHASES RECORDED ON BERMUDA SEISMOGRAPHS

No.	Date	G.C.T. origin time	Latitude	Longitude	Magnitude	Focal depth	Δ	Travel time	Velocity
			degrees	degrees		km.	km.	sec.	km/sec.
1	26 July '50	08–31–28	19 N	68 W	. .	. .	1,430	1,002	1.43
2	6 Oct. '50	11–20–05	17 N	68 W	.	.	1,622	1,095	1.50
3	6 Oct. '50	12–43–03	17 N	68 W	. .	. .	1,622	1,047	1.57
4	1 Dec. '50	14–51–00	14.3 N	47.6 W	7¼	50	2,650	1,770	1.50

Little is known about the spectrum of the energy released by an earthquake in the higher frequencies, owing to the high attenuation in rock at high frequency. Since this limitation is less severe for water, study of T-phase reception by hydrophones can provide important information on this point. The fact that T is readily

[4] Maurice Ewing, G. P. Woollard, A. C. Vine and J. L. Worzel, "Recent Results in Submarine Geophysics," *Bull. Geol. Soc. Am.*, 57: 909–934 (1946).

[5] Frank Press, Maurice Ewing, and Ivan Tolstoy, "The Airy Phase of Shallow-Focus Submarine Earthquakes," *Bull. Seism. Soc. Am.*, 40: 111–148 (1950).

[6] Tolstoy and Ewing, as cited in note 1.

TABLE 3

Pacific T Phases Recorded at SOFAR Stations

Recording station	No.	Date	G.C.T. origin time	Latitude	Longitude	Magnitude	Focal depth	Signal duration	Δ	Travel time	Velocity
				degrees	degrees		km.	sec.	km.	sec.	km/sec.
Point Sur	1	10 Sept. '50	15–15–57	14 S	167 E	7	...	105	9,260	6,353	1.46
Point Sur	2	29 July '50	23–48–58	6 S	155 E	7	...	50	9,751	6,590	1.48
Point Sur	3	4 Dec. '50	16–28–01	5 S	153½ E	7	100	145	9,819	6,665	1.47
Kaneohe	4	18 Jan. '51	21–15–50	52 N	177 W	6¼–6½	...	45	3,770	2,551	1.48
Kaneohe	5	28 Sept. '50	21–47–01	54½ N	134½ W	...	...	25	4,144	2,888	1.43
Kaneohe	6	1 Oct. '50	13–06–14	Queen Charlotte Region		...	...	30	.....	2,780	....
Kaneohe	7	29 Jan. '51	05–02–03	43 N	128 W	...	...	45	3,636	2,515	1.45
Kaneohe	8	29 Jan. '51	05–43–47	43 N	128 W	...	...	85	3,636	2,485	1.46
Kaneohe	9	24 Aug. '50	17–45–34	42½ N	126 W	...	...	30	3,750	2,508	1.50
Kaneohe	10	8 Oct. '50	12–24–17	40½ N	125 W	...	.	60	3,724	2,542	1.46
Point Sur	11	6 Feb. '51	16–33–10	Off Cape Mendocino		...	...	30	.....	432	....
Point Sur	12	6 Feb. '51	17–06–33	Off Cape Mendocino		...	...	30	.....	437	....
Kaneohe	13	29 Sept. '50	06–32–14	19 N	107 W	7	...	60	5,268	3,781	1.39
Kaneohe	14	29 Sept. '50	07–54–22	19 N	107 W	6.2	...	55	5,268	3,788	1.39
Kaneohe	15	3 Jan. '51	12–21–31	18 N	106 W	6¼–6½	...	45	5,394	3,653	1.48
Kaneohe	16	3 Jan. '51	13–04–24	18 N	106 W	6¼	...	25	5,394	3,659	1.47
Kaneohe	17	21 Oct. '50	08–27–13	17½ N	106 W	...	..	45	5,409	3,698	1.46
Kaneohe	18	21 Oct. '50	08–57–10	17½ N	106 W	5¾	...	55	5,409	3,702	1.46
Kaneohe	19	21 Oct. '50	09–42–58	17½ N	106 W	6¾	...	60	5,409	3,701	1.46
Point Sur	20	19 Feb. '51	22–11–54	25 S	117 W	6½	...	70	6,825	4,664	1.46
Point Sur	21	20 Feb. '51	15–24–18	22 S	114 W	6	...	45	.....	4,959	....

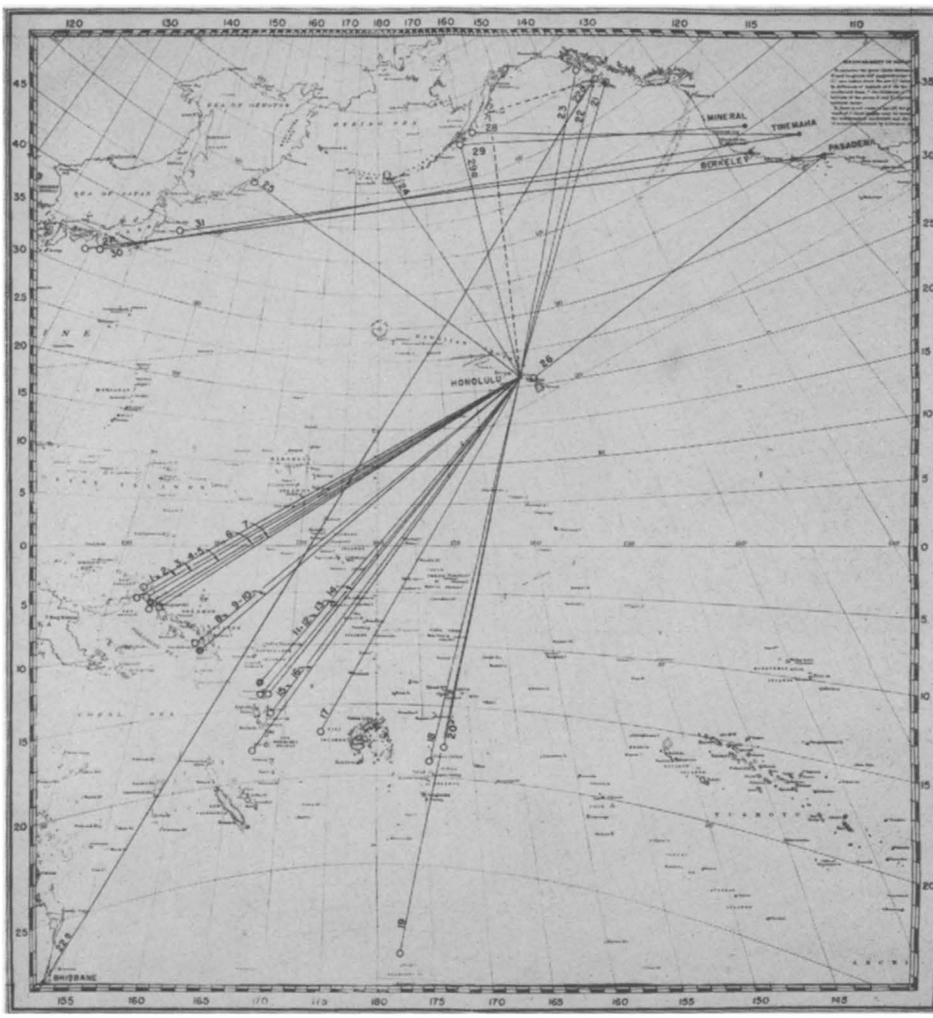


Fig. 2. Paths of Pacific T phases recorded on seismographs.

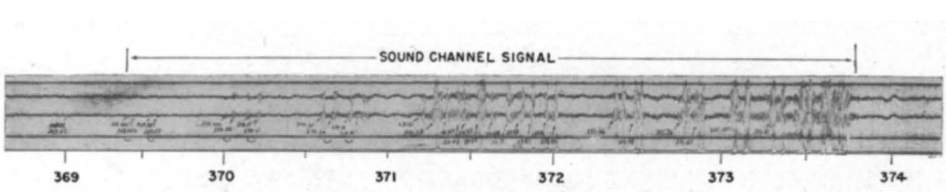


Fig. 3. Seismogram of sound-channel transmission at 300 miles. (4-lb. bomb; bomb depth, 4,000 ft.; hydrophone depth, 3,600 ft.; shot 43° 1601 4/3/44 received at 25° 40′ N, 75° 10′ W.)

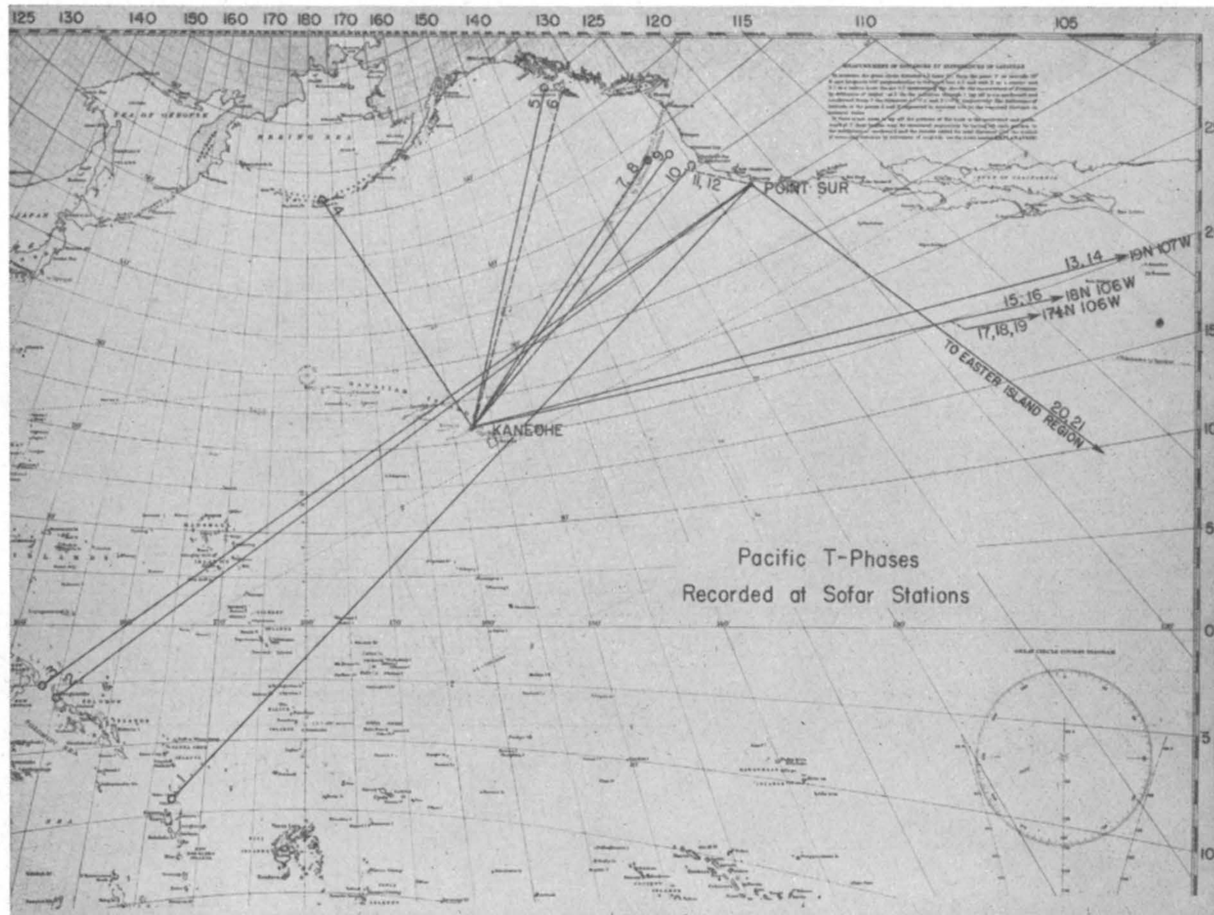
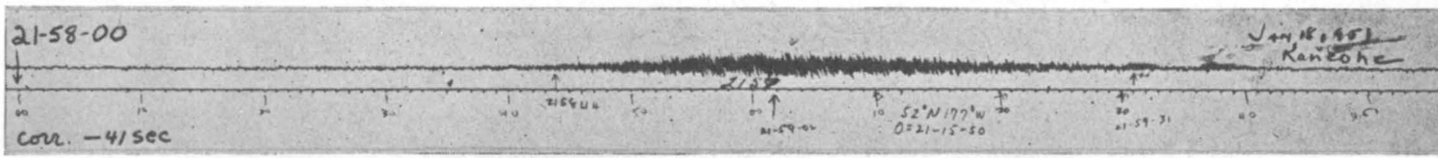
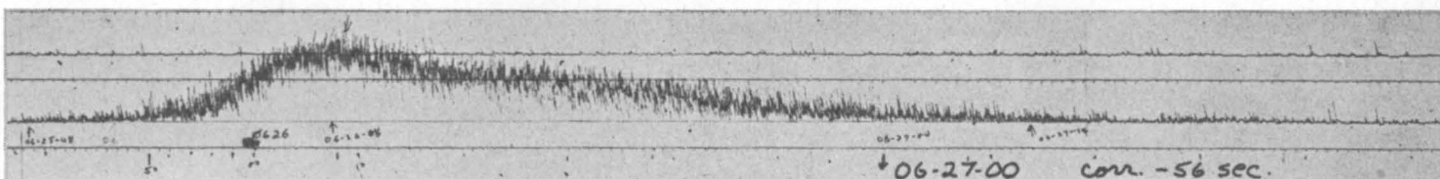


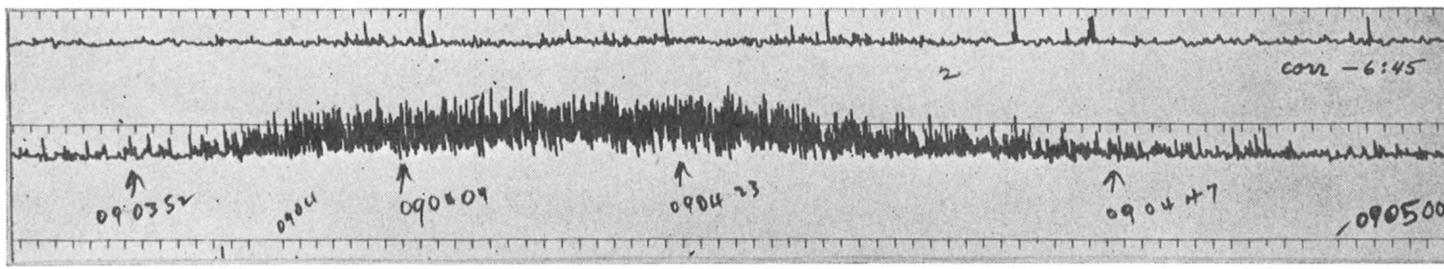
Fig. 4. Paths of Pacific T phases recorded at SOFAR stations. Dashed lines indicate uncertain epicenters.



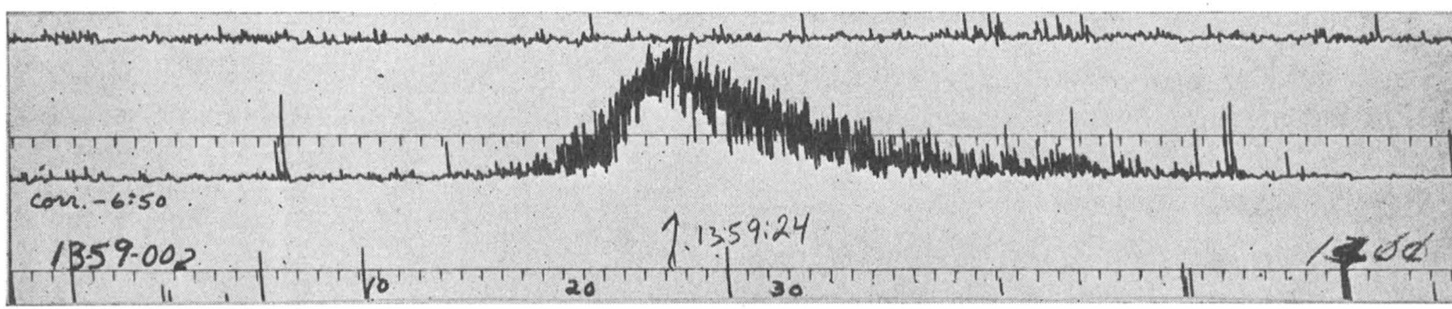
a. **Aleutian Islands earthquake of 18 January 1951 21–15–50.**



b. **Earthquake off Cape Mendocino of 29 January 1951 05–43–47.**

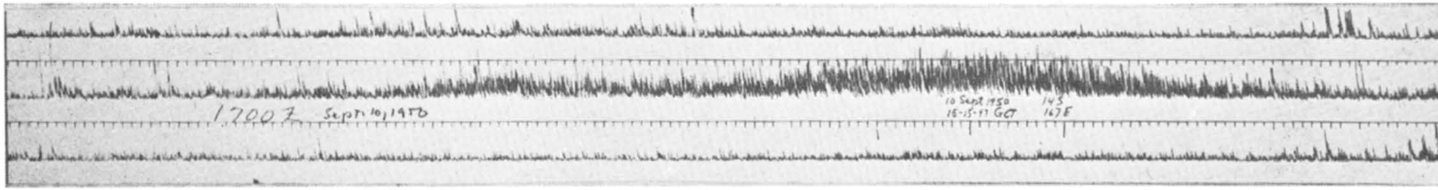


c. Earthquake off Colima, Mexico, of 29 September 1950 07–54–22.

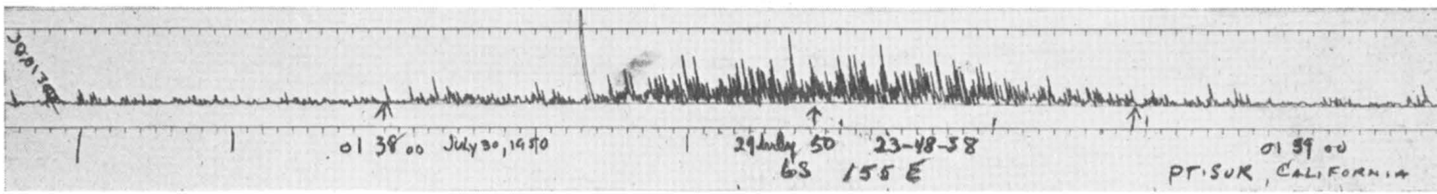


d. Queen Charlotte Islands earthquake of 1 October 1950 13–06–14.

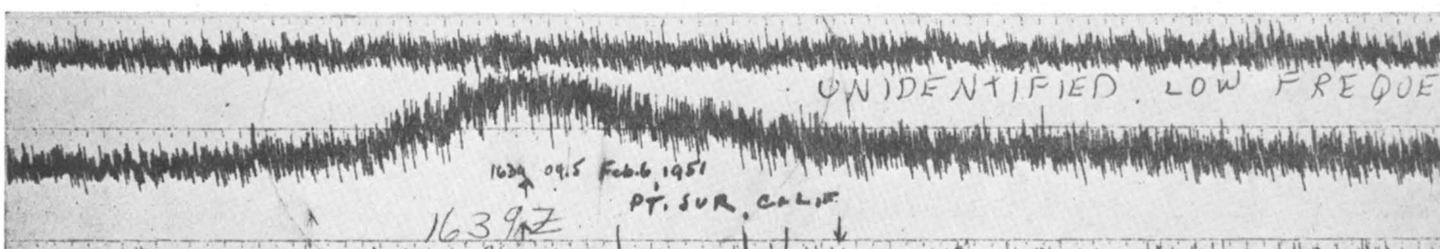
Fig. 5. T phases recorded at SOFAR station, Kaneohe, Oahu.



a. New Hebrides earthquake of 10 September 1950 15–15–47.



b. Solomon Islands earthquake of 29 July 1950 23–48–58.



c. Cape Mendocino earthquake of 6 February 1951 16–33–10.

Fig. 6. T phases recorded at SOFAR station, Point Sur, California.

detected at SOFAR stations is evidence that a considerable amount of energy is propagated through the water with periods much shorter than 0.1 sec.

Assuming the origin times determined by seismograph data for the shocks off the California coast of 6 February 1951 16–33–10 and 6 February 1951 17–06–33 fall respectively along arcs 635 km. and 642 km. from the Point Sur station.

Discussion

The early history of the T phase was discussed in an earlier paper.[7] While that paper was in press, Coulomb and Molard published an account[8] of a short-period phase observed on the seismograms of Martinique from Caribbean shocks. They calculated the velocity of propagation as epicentral distance divided by total travel time. Their velocities showed a considerable scatter, which they attributed to the use of approximate epicenters, and ranged between 1.58 and 2.36 km/sec., averaging 1.854 km/sec. They considered that this rather low velocity phase was transmitted as shear waves (SH) in the layer of sediments on the floor of the Caribbean, and that the velocities were definitely greater than the speed of sound in water. They expressed the opinion that submarine volcanism might generate this motion, realizing that theoretical difficulties were involved. We believe it significant that the great-circle paths from the epicenters to Martinique for all these earthquakes included land or shallow-water parts averaging 25 per cent of the total path. A recalculation of velocities from data given by Coulomb and Molard in which a correction for propagation over land or shallow water (1,000 fm.) at 5 or 6 km/sec. results in a mean velocity for the oceanic portion of the path close to the speed of sound in water.

More recently, Leet, Linehan, and Berger[9] have presented a paper in which they also assign propagation of shear waves through the ocean-bottom sediments as the mechanism for transmission of the T phases from Atlantic and West Indian earthquakes. These phases had been reported since 1935, without explanation of the mechanism of propagation, in the Harvard and Weston bulletins. Byerly (personal communication, May 17, 1951) recently identified T on the Berkeley record of the earthquake of 28 June 1935 in Hawaii.

It is clear that the divergent views expressed by these authors are mainly due to the complications in path, travel time, and land correction introduced by the relatively large proportion of land (or shallow-water) paths, that are present in data of the shocks which they have studied. These complications require corrections which at best are only approximate. The results of Leet, Linehan, and Berger on the land velocity of T are not convincing for the reason that they depend on questionable correlations of events on the Harvard and Ottawa, and Harvard and Weston, seismograms. The new data presented in the present study were selected in order to eliminate these difficulties and to provide an accurate determination of the velocity of T. The consistency of our results as shown by this small scatter, and the excellent agreement of our results with the speed of sound in water, leaves little room for doubt that T is propagated as compressional waves in water; and the similarity be-

[7] See note 1.

[8] "Ondes seismiques au fond de La Mer des Antilles," *Ann. de Geophysique*, T. S., fasc. 3, pp. 1–2 (1949).

[9] L. Don Leet, Daniel Linehan, S.J., and P. R. Berger, "Investigation of the T Phase," *Bull. Seism. Soc. Am.*, 41: 123–141 (1951).

tween reception by SOFAR hydrophones of the T phase and of signals from bombs exploded at the sound channel axis is additional strong evidence. Moreover, the hypothesis that T is transmitted as SH waves in ocean-bottom sediments is immediately ruled out since such waves could not enter the water for detection by the hydrophones.

No destructive tsunamis have been produced by the shocks studied here. Although there has been no opportunity for systematic examination of tide-gauge records to correlate the excitation of T with that of tsunamis, Captain E. B. Roberts of the U. S. Coast and Geodetic Survey has advised us that the Queen Charlotte Islands shock of 22 August 1949, which produced a large T phase, did produce a small tsunami. The correlation between T phase and tsunami excitation for shocks of magnitude about 7 or greater, previously pointed out,[10] can be carried much further when a system for determining the magnitudes of T phases is devised. It is clear that seismographs, in most locations, are orders of magnitude less sensitive for this purpose than SOFAR hydrophones. It is also clear that the sensitivity of each seismograph installation as a T-phase detector depends greatly upon the direction of approach of the disturbance, being subject to acoustical shadows to almost the same degree as SOFAR hydrophones. Thus Berkeley and Pasadena are far more sensitive to shocks from the Hawaiian Islands, the Solomon Islands, etc., than from the rest of the circumpacific belt, particularly Central America and the Aleutians, and Honolulu almost certainly has a maximum of sensitivity to the north and a maximum to the southwest with orders of magnitude difference in the two sensitivities. It appears highly probable that the correlation between T phase and tsunami generation will be greatly improved when proper account is taken of the intensities of the T phase.

Conclusions

1. The T phase is propagated as compressional waves in water.
2. It provides an important tool for epicenter location and for study of depth and mechanism at the focus.
3. SOFAR stations can supply to seismologists an abundance of very precise data for investigations involving the T phase.
4. A SOFAR network could form an extremely useful adjunct to the Pacific tsunami warning system.
5. A T-phase magnitude scale, which must take into account the directionality of each detector and the enormous differences in sensitivity of SOFAR hydrophones and the various types of seismometers, is necessary for seismological applications of the T phase (except epicenter and origin-time determinations) and is urgently needed for direct correlation with tsunami.

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[10] Maurice Ewing, Ivan Tolstoy, and Frank Press, "Proposed Use of the T Phase in Tsunami Warning Systems," *Bull. Seism. Soc. Am.*, 40: 53–58 (1950).

Note Added in Proof

Since installation of short-period Benioff seismographs at the Bermuda-Columbia seismograph station, simultaneous recording of T phases on the Bermuda SOFAR hydrophone and the seismographs have been obtained on numerous occasions. These will be reported in a later paper.

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